

Cost and Performance Comparison of an Earth-Orbiting Optical Communication Relay Transceiver and a Ground-Based Optical Receiver Subnet

K. E. Wilson,¹ M. Wright,¹ R. Cesarone,¹ J. Ceniceros,² and K. Shea³

Optical communications can provide high-data-rate telemetry from deep-space probes with subsystems that have lower mass, consume less power, and are smaller than their radio frequency (RF) counterparts. However, because optical communication is more affected by weather than is RF communication, it requires ground-station site diversity to mitigate the adverse effects of inclement weather on the link. An optical relay satellite is not affected by weather and can provide 24-hour coverage of deep-space probes. Using such a relay satellite for the deep-space link and an 8.4-GHz (X-band) link to a ground station would support high-data-rate links from small deep-space probes with very little link loss due to inclement weather. We have reviewed past JPL-funded work on RF and optical relay satellites, and on proposed clustered and linearly dispersed optical subnets. Cost comparisons show that the life cycle costs of a 7-m optical relay station based on the heritage of the Next Generation Space Telescope is comparable to that of an 8-station subnet of 10-m optical ground stations. This makes the relay link an attractive option vis-à-vis a ground-station network.

I. Introduction

The projected telecommunications demands of future NASA missions from Mars are projected to be tens of megabits per second [1]. These requirements coupled with the limited available radio frequency (RF) spectrum have made optical communications an attractive complement to RF links to meet the communications needs of the early 21st century. Yet, because of its susceptibility to adverse weather, optical communications can provide only 70 percent availability from a single station.⁴ Currently, the proposed

¹ Communications Systems and Research Section.

² Communications Systems and Research Section (currently at Boeing SVS, Albuquerque, New Mexico).

³ Undergraduate Student, Cornell University, Ithaca, New York.

⁴ K. Shaik and M. Wilhelm, *Ground Based Advanced Technology Study (GBATS)*, JPL D-11000 (internal document), Jet Propulsion Laboratory, Pasadena, California, August 6, 1993.

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approach to mitigate these effects is to deploy stations in diverse geographical locations with uncorrelated or anti-correlated weather patterns. Such a strategy requires the deployment of 8 to 10 stations.⁵ An alternative approach is to deploy an Earth-orbiting relay station. This approach will provide over 98 percent availability. The last studies conducted approximately 6 years ago showed that these costs would be approximately twice the cost of a network of ground stations.^{6,7}

With the recent advances in the technology of large space telescopes,⁸ we decided to revisit the cost of the optical communications relay satellite. The objective was to determine whether these advances in technology resulted in cost reductions of the relay satellite and to assess how these new costs compared with those of a 10-m ground-station subnet of comparable availability.

In this article, we report on the comparison of life cycle costs of a 7-m Earth-orbiting optical communication relay transceiver (EOORT) with that of an 8-station linearly dispersed optical subnet (LDOS) and a 9-station clustered optical subnet (COS).⁹ In Section II, we review the results of the previous JPL Earth-orbiting relay satellite studies. In Section III, we review the ground-based LDOS and COS architectures. Costs of the space-based and ground-based configurations are reviewed in Section IV. Technology development issues are discussed in Section V, and the summary and conclusions and are given in Section VI.

II. Results of Previous Earth-Orbiting Relay Satellite Studies

Over the past 25 years, there have been several studies that examined the feasibility and costs of a space-based, Earth-orbiting communication relay satellite. In 1979, John Hunter examined an Earth-orbiting RF relay satellite with receive-only capability [2]. In a 1993 NASA-funded study, Stanford Telecom (STeL)¹⁰ and TRW¹¹ examined a space-based transceiver for optical communications. TRW also compared the performance of an RF configuration with that of direct-detection and coherent optical communication systems. In 1998, JPL's Advanced Project Design Team (Team-X)¹² studied both direct-and coherent-detection configurations for the optical relay satellite. In this section, we analyze and compare the results of these past studies.

A. System Configurations

The configurations of the six systems from past studies and the required performances of the relay satellites are given in Table 1. The configurations ranged from RF relays to direct and coherent detection at optical frequencies. The John A. Hunter results are included here only as a basis for cost comparison. In his 1979 study, Hunter considered a 32-GHz (Ka-band) orbiting deep-space relay station (ODSRS). The ODSRS had a design life of 10 years and was required to meet the then-projected communications needs of missions from 1985 to 2000. It was also required to provide 6-dB improvement over the then performance of the DSN 64-m antenna operating at 8.4 GHz (X-band). The point design was for 125 kb/s from Jupiter (5.2 AU). To meet these requirements, Hunter proposed a 28-m two-reflector Cassegrain antenna design that operated at 32 GHz (Ka-band), 8.4 GHz (X-band), and 3.2 GHz (S-band).

⁵ Ibid.

⁶ DSRSS Concept Design and Technology Report, TR 93063, Stanford Telecom, Reston, Virginia, July 7, 1993.

⁷ Deep Space Relay Satellite System Study Final Report, TRW Federal Systems Division, El Segundo, California, July 22, 1993.

⁸ Goddard-Led Study Team, "The Next Generation Space Telescope," presentation to the NGST Study Office (internal document), NASA/Goddard Space Flight Center, Greenbelt, Maryland, August 21, 1996.

⁹ K. Shaik and M. Wilhelm, op cit.

¹⁰ Stanford Telecom, op cit.

¹¹ TRW, op cit.

¹² R. Oberto, "Earth Orbiting Optical Receivers," JPL Team-X Report (internal document), Jet Propulsion Laboratory, Pasadena, California, April 21, 23, 24, 1998.

Table 1. Configurations and required performances for relay satellites in past JPL studies.

Parameter	RF		Optical			
	Hunter ODSRS	Stel DSRSS	TRW DSRSS	TRW ^a DSRSS	Team-X EOORT	Team-X ^a EOORT
Performance relative to baseline, dB	6	10	10	10	10	10
Baseline, m	64 X-band	70 Ka-band	70 Ka-band	70 Ka-band	70 Ka-band	70 Ka-band
Availability, %	N/A	N/A	N/A	N/A	98	98
Data rate, Mb/s	0.125	1.0	1.2	0.67	10	10
Target planet	Jupiter	Pluto	Pluto	Pluto	Mars	Mars
Antenna size, m	28	16	10	4	7	4
Link margin	0	1	3	3	3	3

^a Coherent-detection scheme.

Deployment of the ODSRS required three shuttle launches: two launches to deliver the hardware to low Earth orbit (LEO), where it was to be assembled and tested, and the third to deliver the booster rocket to propel the ODSRS to a 30-deg-inclined geosynchronous orbit. Ground-station support was to be provided by three widely spaced stations with two-way ranging capability for precise station location of the ODSRS. Data received from the deep-space probe were relayed on a 14-GHz (Ku-band) link from two onboard 2-m antennas to the 5-m Earth station.

STel, TRW, and Team-X all considered a direct-detection scheme for the optical relay satellite. TRW and Team-X also considered coherent-detection systems. The design goal of the STel and TRW studies was to achieve a 10-dB improvement over the 70-m DSN antenna operating at 32 GHz (Ka-band) from Pluto. STel's Deep Space Relay Satellite System (DSRSS) was a 16-m segmented primary receiving telescope to support a 1-Mb/s downlink from Pluto.¹³ The link margin for the STel design was 1 dB. The transmitter at the probe spacecraft was a 20-W, 1064-nm, cavity-dumped Nd:YAG laser coupled to a 40-cm-diameter diffraction-limited telescope. Their relay satellite required two launches. The first was on a Titan III and carried the service module, the apogee and perigee stages, and the payload module core to low Earth orbit. The second, a shuttle launch, carried the optical payload, the solar arrays, and the RF data-relay antennas. Two astronauts were required to assemble the satellite in low Earth orbit. The DSRSS was then to be boosted to a 28-deg-inclination geosynchronous orbit at 70 deg W longitude.

TRW Federal Systems Division's direct-detection DSRSS design called for a 10-m segmented receiving antenna.¹⁴ Using a 7-W frequency-doubled Nd:YAG laser coupled to a 75-cm transmitter, their design achieved 1.23 Mb/s from Pluto (40 AU), 1.77 Mb/s from Neptune (31 AU), and 3.30 Mb/s from Uranus (20 AU), all with approximately a 3-dB margin. A 100-W frequency-doubled Nd:YAlO laser at 540 nm coupled to a 25-cm telescope on the DSRSS served as a beacon and the command uplink to the user spacecraft. This satellite was launched on a Titan IV rocket into low Earth orbit where it autonomously deployed, expanding the receiving antenna to its full 10-m size. An upper-stage rocket then boosted the fully deployed antenna into a geosynchronous orbit.

In 1998, Team-X considered a 7-m aperture telescope for a direct-detection optical relay satellite.¹⁵ The 7-m aperture was selected because its throughput was equivalent to a 10-m ground-receiving telescope

¹³ Stanford Telecom, op cit.

¹⁴ TRW, op cit.

¹⁵ R. Oberto et al., op cit.

operating at 30-deg elevation (72 percent atmospheric transmission at 1 mm) with 70 percent weather availability. Figure 1 is a schematic of the direct-detection EOORT configuration.

The EOORT was required to provide 98 percent availability and support a 10-Mb/s optical link from Mars with less than 18 W of 1064-nm laser power transmitted through a 0.3-m telescope. The receiver also was to support 400 kb/s from Jupiter using a 3-W Nd:YAG laser transmitter coupled to a 0.3-m telescope.

The EOORT receiver based on the Next Generation Space Telescope (NGST) 6.5-m design shown in Fig. 2 is a 7-m telescope that could be appropriately modified to meet the receiver's requirements. A separate 0.3-m-aperture telescope transmitting 100 W of optical power served as a beacon and supported a 1-kb/s command uplink. The satellite was to be launched into geostationary orbit by an Atlas 2AR rocket.

B. Coherent Communications

TRW's coherent-detection system described in Table 1 was also required to provide a 10.4-dB improvement over the 70-m DSN antenna operating at Ka-Band. The design called for a 4-m diffraction-limited monolithic receiving aperture (the maximum diameter that could be accommodated in current launch vehicles) with a homodyne optical receiver and a binary-phase-shift-keyed modulation format. With the probe transmitting 5 W of optical power at the 532-nm wavelength through a 75-cm transmitter telescope,

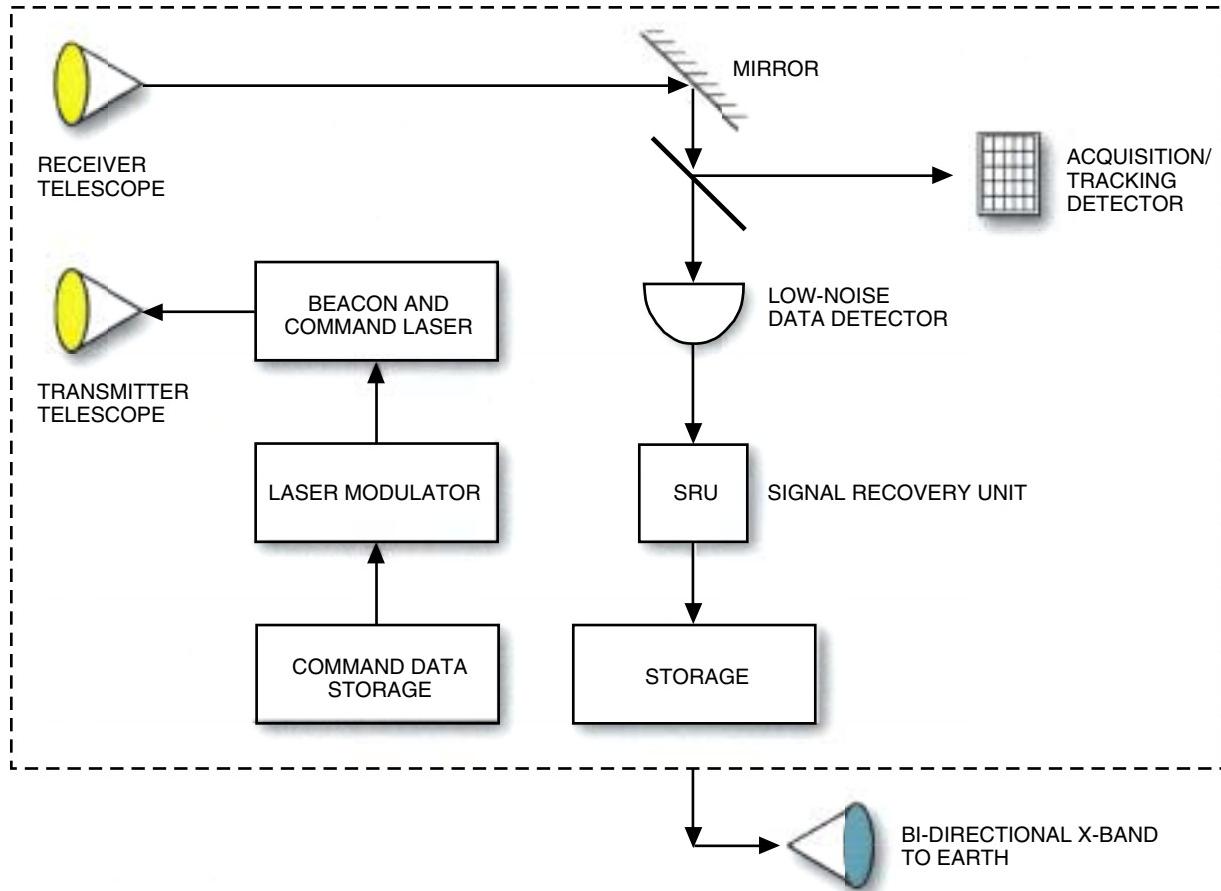


Fig. 1. Schematic of the direct-detection EOORT configuration. The space-based transceiver is designed to provide 98 percent availability on a link from Mars.

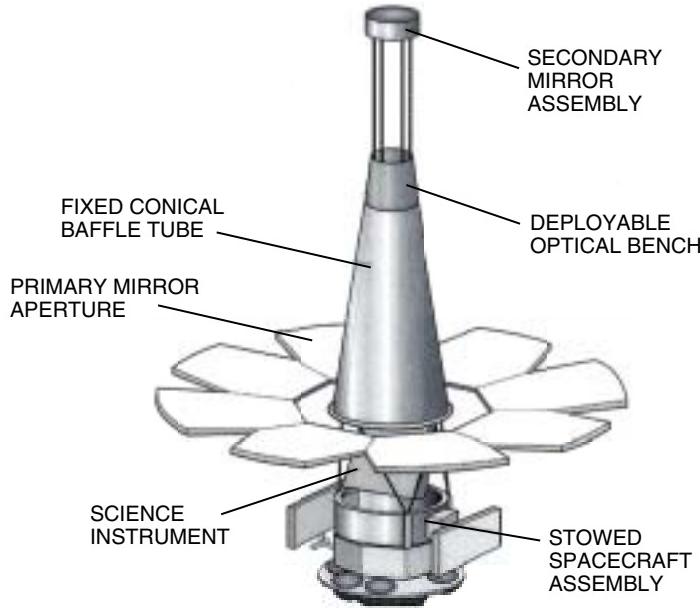


Fig. 2. Concept drawing of the 6.5-m NGST. The EOORT direct-detection receiver would use some of the key technologies of the NGST design.

a 0.67-Mb/s link could be established from Pluto with a 3-dB link margin. The coherent-detection DSRSS also contained a 25-cm transmitter for the 100-W, 540-nm uplink beacon. The coherent communications relay satellite would be launched into its geosynchronous orbit on a Titan IV rocket.

A comparison of TRW's direct- and coherent-detection systems showed that the direct-detection system had 2 to 3 dB better communication performance and 20 percent lower life-cycle cost and lower technology risk than did the coherent-detection system.

Team-X's coherent-detection receiver also was a 4-m telescope designed to support a Mars link. Like the direct-detection configuration, the coherent-detection system was to provide 98 percent availability. The uplink beacon was transmitted to the probe spacecraft using 100 W of 1030-nm optical power transmitted via a 0.3-m sub-aperture of the 4-m telescope. The 4-m transceiver was to be shuttle launched into low Earth orbit. An upper-stage rocket then was to boost it from LEO to a geosynchronous orbit. An X-band omni-directional antenna transmitted the data from the EOORT at 10 Mb/s to an 11-m ground station.

III. Ground Stations

Several subnet configurations for deploying the optical ground stations were considered in the 1994 Ground-Based Advanced Technology Study (GBATS).¹⁶ Two of these configurations, the 3×3 COS and the 8-station LDOS are shown in Fig. 3. In both cases, the stations were separated by greater than 700 km so that there was less than 1 percent correlation in cloud-cover statistics between any two stations.¹⁷ The LDOS affords 97 percent availability when three stations are simultaneously visible from the spacecraft and 66 percent when only two have a direct line of sight. If each site has clear skies 70 percent of the time, then the COS configuration affords 97 percent weather availability.

¹⁶ K. Shaik and M. Wilhelm, op cit.

¹⁷ Ibid.

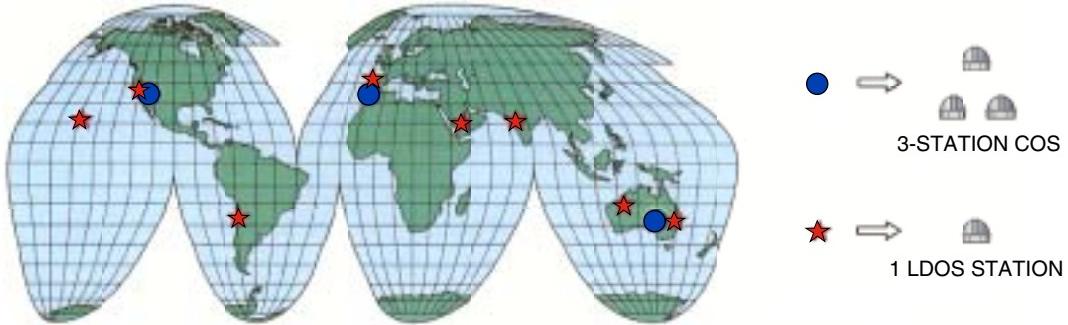


Fig. 3. Map of Earth showing locations of 3X 3 COS and 8-station LDOS.

For an ideal arrangement of sites, i.e., at longitude intervals of 120 deg for the COS and 45 deg for the LDOS, the ground stations afford 100 percent coverage for a telemetry line at 30-deg elevation. In actuality, however, the distribution of the global landmass as shown in Fig. 3 affords less coverage. For the 3×3 COS configuration, it affords only 79 percent coverage as opposed to greater than 95 percent for the 8-station LDOS. For the COS to achieve 95 percent coverage, it would require 12 stations in a 4×3 COS configuration. This of course would be at a much greater cost.

IV. Costs

A. The Earth-Orbiting Relay Satellites

Each of the four relay satellite studies used a different cost estimating approach. Hunter used a bottom up approach, obtaining cost estimates from engineers for each of the seven subsystems that made up the ODSRS. STeL used historical data for the spacecraft modules and received inputs from NASA/Langley to generate a detailed cost estimate for the 16-m receiver. TRW used a GE Price H model. In this model, the most influential inputs that affect the payload cost are weight, manufacturing complexity, engineering complexity, and integration and test complexity. Team-X costs were based on a combination of quasi-grassroots estimates and quotes for mission operations, the launch vehicle, and the various spacecraft subsystems. Cost models were used for other mission components, including payload; systems engineering; integration and test; assembly, test, launch, and operations (ATLO) project office costs; and reserves. Estimates (not the fixed, known costs) were propagated through a series of 500 Monte Carlo simulations that generated the most probable, the maximum, and the minimum cost.

Although their programs ran over several years, Hunter, TRW, and Team-X used 1978, 1992, and 1998 dollars, respectively. These costs were extrapolated to 1998 dollars using the consumer price index (CPI) tables. STeL's estimates were given in real-year dollars and assumed a 3 percent annual inflation rate over the course of the project. To get a meaningful comparison with the cost figures in the other studies, all STeL costs first were converted back to 1992 dollars and then inflated to 1998 dollars using the published consumer price index [3]. The CPI also was used to adjust the TRW and Hunter cost estimates to 1998 dollars. These results are given in Tables 2 and 3 along with the most probable Team-X costs based on 500 Monte Carlo runs. Costs in Table 2 are presented in major categories. The numbers in each category are relative to the corresponding costs ζ in the Hunter study.

From Monte Carlo simulations in the Team-X study, the most probable costs were 0.56ζ . The maximum cost was 0.94ζ , and the minimum was 0.37ζ . The standard deviation was 0.08ζ . Eighty-seven percent of the payload cost was for the receiver and transmitter. The remainder of the instrument was allocated to integration and test (I&T) support, engineering, and management.

Table 2. Life-cycle cost estimates from four JPL-sponsored relay satellite studies.
Costs are relative to the 1979 Hunter RF ODSRS.

Component	Relative costs, \$			
	Hunter ODSRS	Stel DSRSS	TRW DSRSS	Team-X EOORT
Payload	1	0.48	1.23	0.34
Spacecraft and spacecraft ATLO ^a	1	1.78	3.1	1.9
Program management/ system integration	1 ^b	12.0	46.4	17.0
Mission operations	1	0.08	0.29	0.11
Control segment	—	0.07	—	—
Reserves	—	—	0.12 ^c	0.45
Relative total relay satellite	1	0.63	1.37	0.58
Launch and orbit transfer vehicles				
Shuttle	1	2.16	—	—
Titan III	—	0.89	—	—
Atlas 2AR	—	—	—	0.51
Titan IV	—	—	1.42	—
Ground segment	1	1.61	1.17	0.73
Technology development	1	12.26	5.35	—
Relative total system cost	1	1.28	1.42	0.56 ^d

^a Includes spacecraft bus and spacecraft assembly, test, and launch operations.

^b Also includes mission and system design, and test operations.

^c Includes TRW's contractor fee. Stel does not have a fee; their profit is built into their 160% overhead.

^d Standard deviation $\pm 15\%$.

The costs of the Stel and Team-X payload were within 0.14ζ . However, the total costs to deploy these systems differed by a factor of 2.27. The large difference in these costs was due to Stel's pre-development and launch costs. Approximately 74 percent of the pre-development costs in the Stel satellite were for the optical payload. Such large pre-development costs were avoided in the EOORT by using the heritage of the NGST design. In addition, the Stel relay satellite required a Titan III launch, followed by a shuttle launch of additional hardware and an in-orbit astronaut assembly. In contrast, the EOORT was launched on a single launch vehicle and autonomously deployed in orbit.

TRW's payload cost was 1.23ζ , approximately 2.5 times that of Stel's and about 3.5 times that of Team-X's. The break out of the TRW payload costs was as follows: 0.9ζ for the receiver optical telescope assembly, 0.1ζ for the beacon subsystem, and 0.12ζ for the acquisition, tracking, and pointing subsystem. The communications subsystem, the payload mode control, and payload module integration and test made up the remaining costs. Neither the Hunter nor the Stel study carried reserves. The reserves in the TRW and EOORT Team-X, therefore, were referenced to the Hunter payload costs. These reserves were 12 percent and 45 percent, relative to their respective payloads.

Table 3. Life-cycle cost estimates for the TRW and Team-X coherent-detection relay satellites. Costs are relative to Hunter in Table 2.

Component	Relative costs, \$	
	TRW DSRSS	Team-X EOORT
Payload	1.97	0.45
Spacecraft and spacecraft ATLO	2.76	2.36
Program management/system integration	0.29	0.13
Mission operations	1.75	0.43
Reserves	0.19 ^a	0.19
Total relay satellite relative to ODRS	1.81	0.71
Launch vehicle:		
Shuttle	—	0.77
Titan IV	1.43	—
Ground segment	1.17	0.71
Pre-Development	5.38	—
Total relative to ODRS	1.75	0.72 ^b

^a Contractor fee.
^b Standard deviation $\pm 15\%$.

B. Coherent Optical Communication Receiver

TRW and Team-X cost estimates for the coherent receiver payload are given in Table 3. The total cost was 1.81ζ of the corresponding Hunter payload costs. The spacecraft cost was 77 percent of the overall system cost. The remaining costs were broken down as follows: launch costs 16 percent, pre-development costs 4 percent, and ground segment costs 3 percent. Of the spacecraft costs, 66 percent was for the optical communications payload. The optical communications payload costs were broken down as follows: 85 percent for the optical telescope assembly, 5 percent for the beacon assembly, and 4 percent for the acquisition, tracking, and pointing subsystem. The communications subsystem, the optical front end, the payload mode control, and payload module integration and test made up the remaining 6 percent of the costs.

The Team-X cost estimate for the coherent-detection relay satellite was 0.72ζ , 41 percent of the TRW estimate. Of this, 75 percent of the cost was for the space system (i.e., satellite and payload), 21 percent was for the shuttle launch, and the remaining 4 percent was the cost of the ground segment. The optical communications payload cost was 39 percent of total space systems cost. The Team-X study relied on advanced telescope technology. The weight of the 4-m telescope was based on the NGST target mass density of 15 kg/m^2 . The total weight of the telescope thus was estimated at 188 kg. In comparison, the primary and secondary of the TRW telescope weighed 760 kg, about a factor of four more than the Team-X design. Not coincidentally, the TRW cost estimate generated by the GE Price H model depended strongly on mass of the payload and was approximately a factor of four times that of Team-X. Therefore, one would expect the TRW estimates to approach those of Team-X for a lightweight NGST-type telescope.

C. Optical Ground-Station Costs

Table 4 gives a comparison of the 10-year life-cycle costs for the 9-station (3×3) COS and the 8-station LDOS. The design of the 10-m optical receiver has been described in detail in an advanced communications benefit study (ACBS)¹⁸ and will not be repeated here. Instead, we present the updated cost estimates of the 10-m receiver facilities, the transmitter facilities, and the high-power uplink laser ground stations from the Telecommunications and Mission Operations Directorate (TMOD) road map.¹⁹ The cost figures given are relative to 10-m telescopes such as the Keck and Gran Telescopio CANARIAS (GTC) in the Canary Islands without adaptive optics. The assumptions made in developing the cost estimates of Table 4 were as follows:

- (1) Each station consists of a 10-m photon-bucket receiver and a 1-m class transmitter telescope with laser.
- (2) The first station is located in the continental United States at a cost of approximately 51 percent of current 10-m telescopes.
- (3) Subsequent U.S.-based stations each cost approximately 10 percent less.
- (4) Estimated costs of foreign stations is approximately 23 percent more than U.S. stations.

Table 4. Comparison of 3×3 station COS and 8-station LDOS costs.

Item	Relative costs, \$	
	3×3 station COS	8-station LDOS
Stations	4.9	4.4
10-year operations cost ^a	0.53	0.52
Common facilities ^b	0.23	0.23
Total relative to Hunter total	1.75	0.71

^a Operations and facilities costs as shown are a percentage of the station costs.
^b Includes network operations control center, software development, ground communications, facility support, etc.

V. Technology Development

The technology developed for the NGST was designed for 5-year operation and the design optimized for 1,000-nm to 5,000-nm operation. The EOORT will need to have a 10-year operational life, and the modifications to the NGST design may be needed to support this extended life and the wavelength range of 500 nm to 2000 nm. Key technologies needed to support the EOORT follow.

A. 7-Meter Space-Based Telescope

A 7-m space-based telescope that is capable of maintaining the required optical figure under a near-Earth thermal environment is needed. NGST is designed to operate in a more benign thermal environment

¹⁸ ACB Study Team, "Advanced Communications Benefit Study, Mars Mission Study Results," JPL viewgraph presentation (internal document), Jet Propulsion Laboratory, Pasadena, California, April 28, 1995.

¹⁹ C. Edwards, "NASA's Deep Space Telecommunications Roadmap," presented to NASA (internal document), Washington, D.C., January 22, 1998.

at L2. Both direct solar and Earth re-radiated thermal energy will increase the EOORT's temperature and, if not removed from the telescope, will degrade the receiver's performance.

B. Large Lightweight Sunshade

A large lightweight sunshade to allow operation at smaller Sun–EOORT–probe angles is needed. To support a large class of missions over extended operational periods, the EOORT will need to track probes at low Sun–Earth–probe (SEP) angles. Lightweight sunshields that keep the Sun off the telescope primary when tracking at low SEP angles will need to be designed.

C. Efficient, High-Power, High-Beam Quality, Space-Based Lasers for the Uplink Beacon

There are high-power laser development projects ongoing in several government programs for other customers, yet efficient generation of high-power lasers with near-diffraction-limited beam quality is an important area of technology needed for deep-space communications. Near-diffraction-limited laser beams provide a higher level of tracking signal at the probe. Theoretically, greater than 20 percent wall plug efficiencies should be achievable. However, typical efficiencies for near-diffraction-limited high-power diode-pumped solid-state lasers suitable for deep-space communications are currently about 7 to 8 percent at IR wavelengths [4].²⁰ These lasers are approximately a factor of two to three less efficient when frequency doubled to operate in the visible.²¹

Nd:YLF (1050 nm) and Yb:YAG (1030 nm) are candidate lasers that are efficient. Yet, it is uncertain whether they are sufficiently separated from the 1064-nm Nd:YAG wavelength to allow the required transmit/receive isolation. High-power Yb:YAG operation has been demonstrated. Thermal lensing limited the beam quality to approximately 5x diffraction-limited beam divergence.²² Preliminary research results show that thermal lensing, which is the primary cause of poor beam quality, can be mitigated by operating the Yb:YAG laser at temperatures below 100 K.²³

D. High Quantum Efficiency (QE), Low-Read Noise, Near-IR Focal-Plane Arrays

The EOORT will need to track the 1064-nm downlink signal from the probe to maintain the link. Development of high quantum efficiency, low-noise, IR-sensitive array detectors will reduce the required optical power from the probe. HgCdTe and InGaAs focal-plane arrays have intrinsically high QEs (~ 0.8) in the IR. However, when fabricated as 15- to 20- μm pixelized windowed devices, the effective QE drops to 30 to 40 percent.

E. High Quantum Efficiency, Low-Noise, Near-IR Data Detectors

The sensitivity of the receiver is an area where significant gains in link margin can be realized. For the optical deep-space channel, improved receiver sensitivity is achieved by higher QE of the data detector at the transmitter wavelength, lower intrinsic noise, and higher receiver gain.

F. High-Quality, Low-Mass, Thermally Stable Transmitter Telescope

To maximize the beacon power at the probe, high-power, high-spatial-quality lasers, and low-loss high-quality optics are needed. The laser must have near-diffraction-limited beam quality, and the transmitter optics must be free of aberrations that would degrade the beam divergence.

²⁰ C. Bibeau, R. Beach, C. Ebbers, M. Emanuel, E. Honea, S. Mitchell, and J. Skidmore, "Performance of a Diode-End-Pumped Yb:YAG Laser," 1997 Diode Laser Technical Review, Albuquerque, New Mexico, June 9–12, 1997.

²¹ S. Aiken, F. Way, T. Crow, B. Hoden, and J. Chavez, "High PRF, 100 W, Frequency-Doubled Nd:YAG Laser," 1997 Diode Laser Technical Review, Albuquerque, New Mexico, June 9–12, 1997.

²² C. Bibeau et al., op cit.

²³ T. Y. Fan, "Laser Development at MIT Lincoln Laboratory," Lincoln Laboratory, Massachusetts Institute of Technology, presented to JPL (internal document), Pasadena California, January 22, 1999.

G. High-Quality, Space-Qualified Optics Capable of Supporting High Optical Power Densities

The beacon lasers are both high-average-power and high-peak-power devices. Optical coatings and components must withstand both the thermal effects due to the high average powers and the potential damage effects of the high peak powers.

Although not considered in the EOORT design, a 10-Mb/s data link from Mars will require the development of a high-power, pulsed modulation scheme such as cavity dumping that can generate high peak powers at megahertz rates. Such lasers currently are under design by Hughes Research Laboratories (HRL) Malibu under a NASA Research Agreement.

VI. Summary and Conclusion

We have reviewed past JPL-supported work on space-based optical communications relay satellites and on the ground-based optical subnets, and have compared the 10-year life cycle costs of the space-based and ground-based systems. The results of the 1998 JPL Team-X study show that the estimate of the most probable cost of a 7-m direct-detection telescope on the relay satellite is comparable to the cost of nine 10-m ground stations built and operated over 10 years. The JPL relay satellite cost estimates relied on NGST lightweight mirror technology and were a factor of two less than those of the 1992 TRW and STeL studies. This study reviewed the cost of the eight-station LDOS and the nine-station COS architectures and found that the cost of the COS system was about 10 percent higher than the LDOS, the small difference due to the cost of an extra station and the slightly higher cost of foreign stations.

Although the EOORT provided greater availability at a life-cycle cost less than that of the ground-based LDOS configuration, it is a single station and can track only one spacecraft at any given time. In contrast, the eight-station LDOS configuration can provide comparable coverage, although at slightly less availability, to a single probe, or it can track up to eight different probes. An optical communications development path that begins with a certain number of ground stations that leads towards the deployment of an EOORT can capture the advantages of the space-borne platform while providing a certain degree of multi-spacecraft support from the ground stations.

Several technology areas need to be developed to support both the ground- and space-based receivers. Technology development in the areas of efficient laser sources, high-speed modulation of solid-state laser sources, focal-plane arrays, and low-noise, high-quantum-efficiency detectors will be needed. Future planned work includes the following:

- (1) Exploring such a hybrid configuration with the intent of identifying a configuration that contains fewer ground stations at less than the aggregated cost of the EOORT and the eight-station LDOS described here.
- (2) Establishing a higher level of involvement in the Air Force's and industry's high-power laser programs.

VII. Addendum

Since this study was performed, the NGST project has become the James Webb Space Telescope (JWST). TRW of Redondo Beach, California (currently Northrop Grumman Space Technology), was awarded a \$824.8M contract by NASA to build the JWST. The telescope is scheduled for launch on an expendable launch vehicle in 2010.

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